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Pool Boiling Of Deionised Water Over Polyurethane Coated Surfaces

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ABSTRACT

Preliminary investigations are done to cater the possibility of the use of the polyurethane coating for the pool boiling heat transfer augmentation. Experiments have been done on the bare stainless steel heater and stainless steel heaters coated with polyurethane coatings of different thicknesses, by boiling deionised water at constant atmospheric pressure. Contact angle formed by the deionised water over the test specimen are experimentally measured and from these values the solid-liquid surface energy values have been calculated. It has been found that the polyurethane coating has increased the solid-liquid surface energy and the heat transfer. Recommendations for the future inspections with relevance to finding an ideal heat transfer enhancer coating are putforth.

Keywords: heat transfer, pool boiling, contact angle, surface energy

INTRODUCTION

Boiling is applicable in various fields such as chemical engineering, mechanical engineering, nuclear engineering etc. The objective of the engineer in all these fields is to design a system which will transfer heat with minimum possible temperature difference. For this particular purpose, various researchers have proposed different heat transfer augmentation techniques which could be classified as passive and active techniques [1-5]. Polymer coating is one such passive heat transfer augmentation technique used by some researchers [5-15] and with the advent of their research Polytetra-fluroethylene [PTFE$^{@}$] i. e. Teflon emerged as one of the coatings that can be utilized for heat transfer augmentation. However, the suitability and the feasibility studies recommend the need of alternative coatings over the Teflon that can enhance the heat transfer optimistically. The required peculiarities for the alternative coatings are durability, longetivity, ability to work at different temperatures, pressures and heat flux levels, ability to adopt the variations in heat flux, pressure and temperature magnitudes, workability with different liquids and parent heat transfer surfaces at various operating conditions and under the influence of different surrounding fields, ecofriendliness, manufacturability, economy etc.

In this paper, work done on assessing the possibility of the use of the polyurethane coating for enhancing the pool boiling heat transfer of water is described. Polyurethane coating is cheaper, easily manufacturable, easily applicable and ecofriendly. The durability tests, adoptability at various operating pressures, temperature and heat flux situations etc. could not be studied in the present chapter of the work and are aimed in the future.

EXPERIMENTAL SETUP and EXPERIMENTAL PROCEDURE

The investigation of the pool boiling of deionised water over the stainless steel surface and the polyurethane coated stainless steel surfaces has been planned. The laboratory grade experimental kit used for the present study has been consisting of a well insulated (asbestos wrapping) container with a glass window, electrically heated stainless steel heater, a condenser, bubbler, temperature and pressure measuring instrumentations, dimmerstat (to vary the Wattage) etc. as shown in the Fig. 1.

The stainless steel heater has been 0.25 m in length and 0.03 m in outer diameter. A domestic cartridge heater has been used to supply the heat to the heater. The cartridge heater has been prepared by winding a nichrome wire over a porcelain tube. The heater has been open at one end so that it could be affixed to the vertical rod, with the help of the threads, so as to align itself in horizontal position. Heater and the vertical rod have been insulated from each others with the help of a thin mica sheet. The vertical rod could be moved vertically up and down thus enabling to change the depth of the heater in the deionised water pool.

The outer surface of the heater has been prepared smooth by turning, polishing and then rubbing (with the help of a standard grade emery paper). Then all the stainless steel heaters selected for the experiments have been cleaned with filtered deionised water. Then those have been tipped with cotton plugs soaked in filtered deionised water. Afterwards they have been retipped with the dry cotton plugs and immediately those have been given coatings of the various thicknesses. Polyurethane coating (name of the Paint: Touchwood-Asian Paints (I) Ltd.) of various thicknesses has been given over the heater surfaces using the paint brush manually. A single person hand has been incorporated to apply the coatings evenly in the same fashion. The bare copper coils after the application of coating have been dried in open atmosphere. The four heaters have been thus prepared for the experiments and are specified in table 1.

After drying, the thickness of coating has been measured with the help of a micrometer (MituToyo make) randomly at several locations of the heater surfaces and the average value of the thickness (no significant variations have been found) has been taken. Afterward these coated coils have been immediately used for the contact angle measurement. These contact angle measurements of the filtered deionised water formed over the heater surfaces have been done with the help of the sessile drop method produced by means of a locally available clean and new syringe everytime. The contact angle measurement system is as shown in Fig. 2. Droplet size of 0.3-0.4 cm has been used for the contact angle measurement. Bubbles of filtered deionised water have been formed at several locations over the entire heater surface and the average value has been taken.

Fig. 1 Figure of the experimental setup
(Figure not to scale)

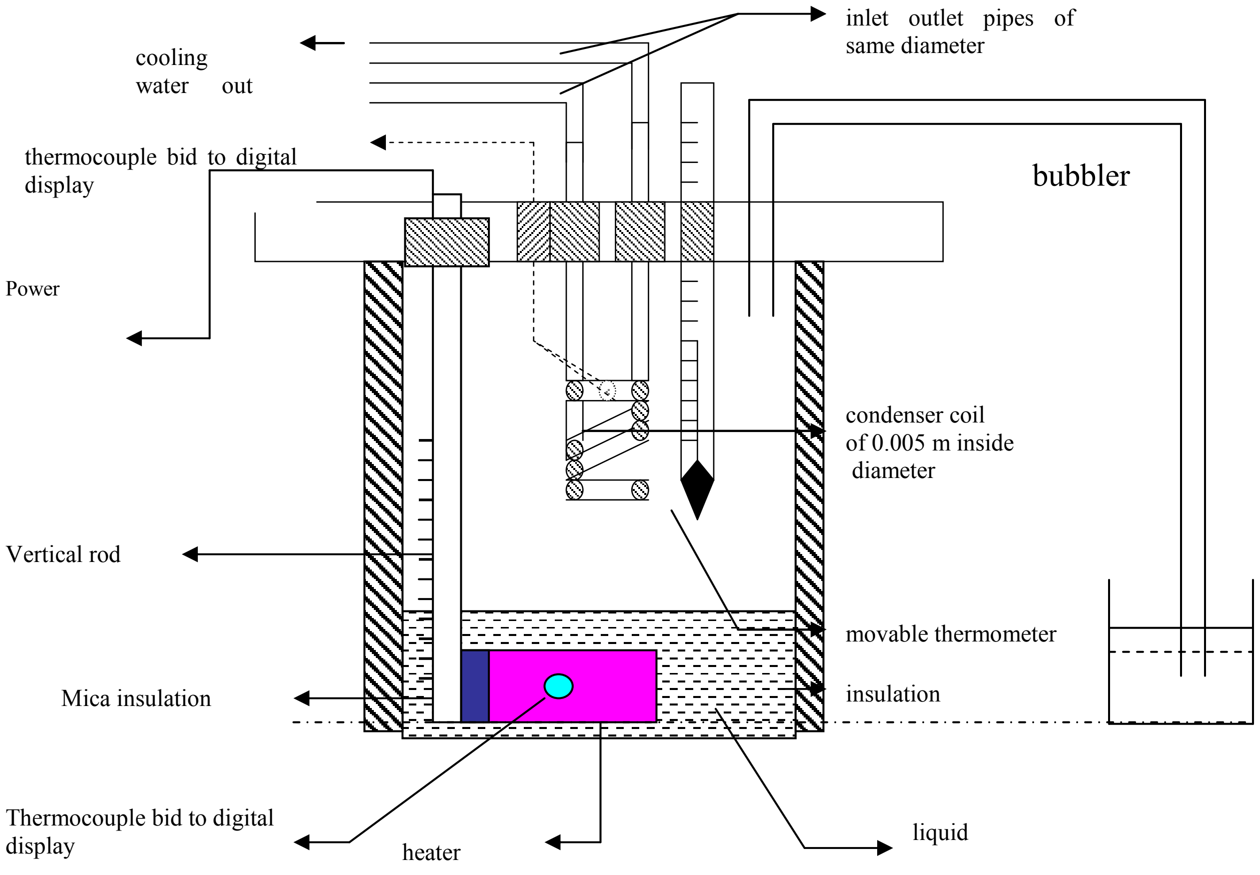


Table 1. Specifications of the heaters used for the experimentations

Heater No.	Specifications
1	Bare heater of 0.03 m diameter × 0.25 m length, with no coating over it
2	heater of 0.03 m diameter × 0.25 m length, with polyurethane coating of 0.000112 m thickness over the heating surface
3	heater of 0.03 m diameter × 0.25 m length, with polyurethane coating of 0.000215 m thickness over the heating surface
4	heater of 0.03 m diameter × 0.25 m length, with polyurethane coating of 0.000240 m thickness over the heating surface

While measuring the contact angle distances among the light source and the heater surface, heater surface and paper have been kept constant along with their heights and it has been well ensured that the light rays are parallel to each others and the light source, the bubble and the paper image are in the same plane parallel to the ground. The obtained values of the contact angles are given in Table 2.

Fig. 2 Contact angle measurement system

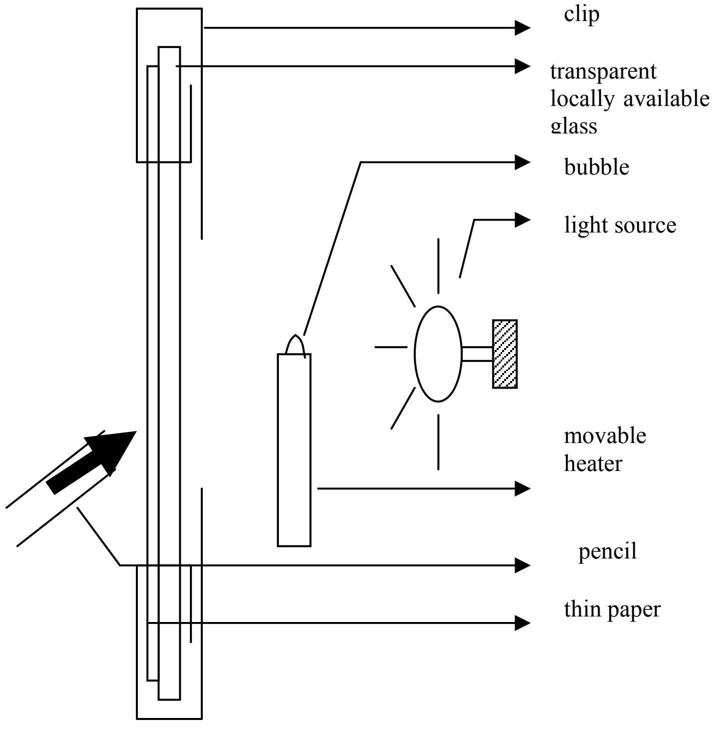
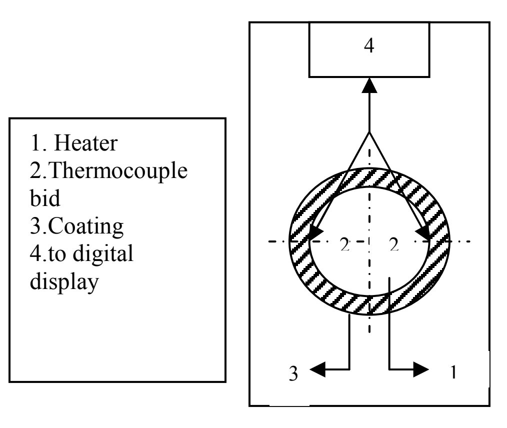


Table 2. Contact angle information of different heaters used for the experiments

Heater No.	Measured Contact angle (^{0})	Calculated surface energy (N/m) [based on the average value of the contact angles]
1	**97** (97, 96, 95, 99, 97)	0.02266159
2	**107** (107, 106, 109, 105)	0.030069863
3	**114** (111, 114, 115, 116)	0.035627088
4	**126** (125, 126, 128)	0.045382718

Calibrated copper-constantan thermocouples (connected to a digital display) have been used to measure the heater surface temperature at two locations as shown in Fig. 3. The thermocouple bids have been pasted on the heater surface but underneath the coating as shown in Fig. 3. The liquid temperature has been measured with the help of a standard mercury glass thermometer. Due care has been taken to keep the safe distance between the heater and the thermometer so that the readings of the thermometer don't get influenced because of the heater superheated boundary layer formation effects. While measuring the temperature of the liquid, the thermometer has been moved to various positions (bottom, top and side portions of the liquid bath) and the average temperature is noted. The digital temperature setup comprising the thermocouples and the thermometer have been well accurate to show temperature upto the accuracy of 0.1^0 C and 1^0 C respectively. A laboratory grade pressure gauge has been incorporated to measure the pressure inside the boiling kit.

Fig. 3. Heater cross-section



Standard boiling procedure has been followed for the experimentations. Initially the container has been washed with the help of filtered deionised water thoroughly and then allowed to dry. Then the rod, with test heaters affixed to it in the horizontal position, has been adjusted to its location, followed by manual addition of the measured quantity of filtered deionised water. The filtered deionised water has been added gently inside the container. Initially all the heaters have been thermally stabilized by submerging them in the liquid pool for around 24 hours and then boiling vigorously for about next 24 hours which ensured degassing and passing the vapour out through the bubbler. The experimentations have been performed at constant atmospheric pressure several times till reproducible datapoints are obtained. The deionised water has been then boiled at constant wattage of 1000 W and at the steady state conditions the temperature readings are noted down. The uncertainty analysis pertaining to this experiments are given in Table 3.

Table 3. Uncertainty analysis

quantity	**Instrument used**	**uncertainty**
Length of the heater	Micrometre (MituToyo)	1 µm
Diameter of the heater	Micrometre (MituToyo)	1 µm
Thickness of the coating	Micrometre (MituToyo)	1 µm
Contact angle	Protractor	1°
Temperature of the heater	Digital display	0. 1° C
Temperature of the liquid bath	Liquid thermometer	1° C

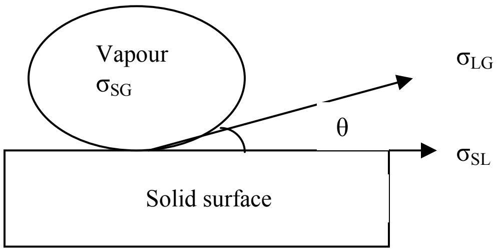
OBSERVATIONS and DISCUSSION

In order to compare the quantity and the quality of the heat transfer augmentation, a suitable criteria is required with the help of which boiling behaviour could also be predicted. Moreover there is a need of a suitable platform over which the boiling performance can be studied and the safe and the efficient heat transfer device designing could be done. Vachon *et al.* [12], Shoji and Zhang [16] tried to explain the behaviour of the heat transfer enhancement in terms of the contact angle but concluded that it is not the only parameter complete in itself, for the enhancement explanations. Hinrichs *et al.* [9] tried to use the parameter of the surface energy but could not explain the increase and the decrease of the heat transfer with change in coating thickness. More over the data available in the current literature base is scanty to have the concrete conclusions drawn.

In the present work, the contact angle formed by the deionised water over the experimental heaters has been measured and then from the contact angle measurement, the surface energy value has been calculated. The contact angle information and surface energy calculations are explained below:

Considere a bubble at a stationary solid surface as shown in Fig. 4.

Fig. 4. Bubble contact angle



The contact angle θ is related with the surface energies σ_{SL} σ_{SG} and σ_{LG} by Young's Eq. (1) as follows:

$$\sigma_{LG} \cos\theta + \sigma_{SL} = \sigma_{SG} \qquad (1)$$

From [16-19],

$$\Phi = 1 - 0.0075\, \sigma_{SL} \qquad (2)$$

where Φ is the Good's interaction parameter and is expressed as

$$\Phi = \{(\sigma_{LG} + \sigma_{SG} - \sigma_{SL})/\, (2\, (\sigma_{LG}.\, \sigma_{SG})^{1/2})\} \qquad (3)$$

With the help of Equations 1-3, the solid-liquid surface energy values have been calculated from the contact angle information collected from this experimentation.

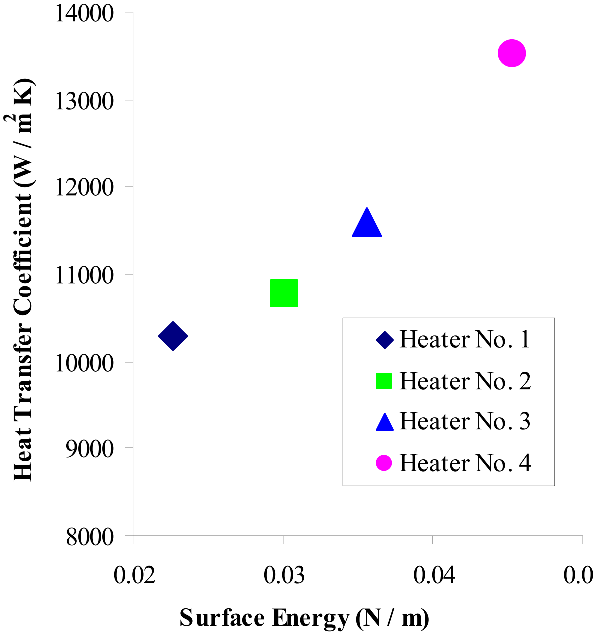
The heat transfer coefficient values have been calculated by using the following formula due to Sir Isaac Newton:

$$h = \{(Q/A)/(T_w - T_l)\} \qquad (4)$$

The heat transfer coefficient values have been calculated for the bare stainless steel heater, polyurethane coated stainless steel heaters of different thicknesses and have been plotted against their respective surface energy values in Fig. 5.

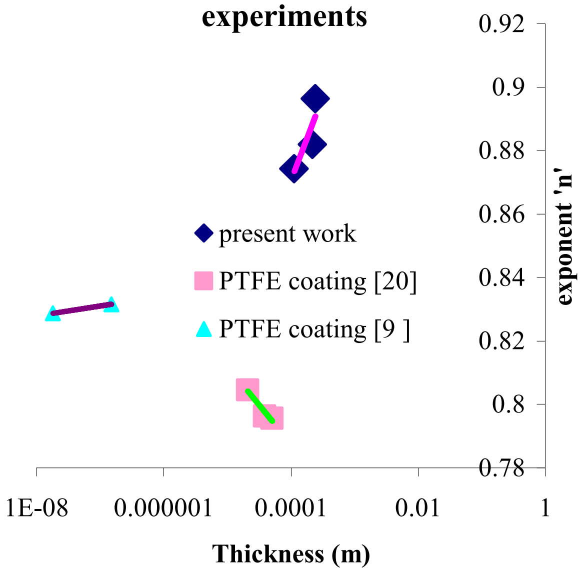
From Fig. 5, it is observed that with the increase in the solid-liquid surface energy the heat transfer coefficient has increased. The solid-liquid surface energy values of the stainless steel heaters coated with the polyurethane coatings of different thicknesses have been found to be more than that of the bare stainless steel heater. It is concluded that the application of the polyurethane coating has increased the solid-liquid surface energy of the heaters in comparison to the bare heater which in turn has resulted in increase in the heat transfer coefficient. Moreover it is found that, with the increase in the coating thickness, the solid-liquid surface energy value has also increased thus ultimately enhancing the heat transfer coefficient.

Fig. 5. Variation of heat transfer coefficient with surface energy



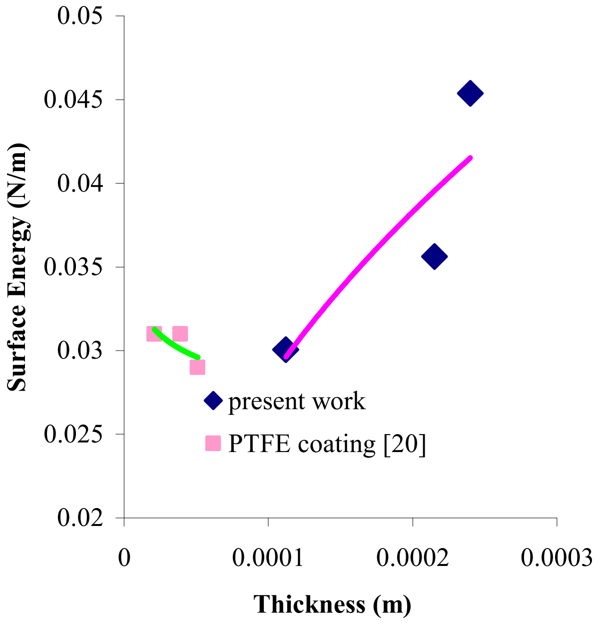
It is well established that $h\ \alpha\ q^n$. The values of the exponent, n, obtained with the present study of polyurethane coating and from [9] and [20] of PTFE coatings are compared vis-à-vis the coating thickness in Fig. 6.

Fig. 6. Comparison of the exponent 'n' obtained with different experiments



It has been seen from Fig. 6 that, the rate of increase of the exponent 'n' with increase in the coating thickness, obtained from the present study of polyurethane coating is more than those obtained with the PTFE coatings. Also it has been observed from Fig. 7 that rate of increase of the solid-liquid surface energy with the polyurethane coating thickness is more than the rate of increase of the solid-liquid surface energy with PTFE coating thickness. The current literature base doesn't contain adequate datapoints in this regard for more study.

Fig. 7. Comparison of the solid-liquid surface energy obtained with different experiments



In the present study, the durability test, coating strength testing for various operating conditions couldn't be done and is the future programme of the study. In the current study programme, the coating is given manually. The effect of the different coating techniques is also a separate matter of study and requires further efforts.

CONCLUSION

An experimental investigation is done to assess the possibility of the use of the polyurethane coating for enhancing the pool boiling heat transfer. Deionised water is boiled over the bare uncoated stainless steel heater and over the manually painted polyurethane coated (of different thicknesses) stainless steel heaters at constant atmospheric pressure and at a constant wattage of 1000 W. The contact angle measurements are done over the test specimen and the solid-liquid surface energy for the respective specimen is calculated. It has been found that with the application of the polyurethane coatings the heat transfer coefficient has increased as compared to that obtained with the bare stainless steel heater. With successive application of polyurethane coating the solid-liquid surface energy has been found increased which ultimately enhanced the heat transfer coefficient. The comparative study of the polyurethane and PTFE coatings revealed that, the rates of increase of 'n' and the solid-liquid surface energy, with the coating thickness, are more for the polyurethane coating than those of the PTFE coatings.

Polyurethane is a cheaper, easily manufacturable and easily applicable paint that has augmented the pool boiling heat transfer. More study pertaining to durability, longetivity, abilities to work at various steady and unsteady operating conditions, suitability for different fluids and heater materials is planned in future. The study of the effect of the different coating techniques over the pool boiling heat transfer is in need of attention and is also aimed.

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NOMENCLATURE

θ : Contact angle [deg];
σ_{LG} : Liquid-gas surface energy [N / m];
σ_{SG} : Solid-gas surface enrgy [N / m];
σ_{SL} : Solid-liquid surface energy [N / m];
h : heat transfer coefficient [W / m^2 K];
Q : Heat transferred per unit time [W];
A : area of heat transfer [m^2];
T_w : wall temperature (average) [K];
T_l : liquid pool temperature (average) [K].

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